

A MODEL OF THE SPATIAL AND TEMPORAL VARIATION OF THE
URANUS THERMAL STRUCTURE

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Seasonal variability of the temperature structure of Uranus is modeled for all latitudes in the 10^{-4} to 2 bar pressure range in anticipation of the Voyager encounter in January 1986. Atmospheric heating in the model results on the one hand from an internal heat source and, on the other hand, from absorption of solar energy by methane and by non-conservative aerosols located between the 0.5 and 2 bar levels. Various cases for the behavior of the internal heat flux are investigated, such as constant with latitude or constrained to yield a time-averaged thermal emission independent of latitude. Meridional transport of heat in the stably stratified atmosphere is not taken into account. The results indicate that at the Voyager encounter time, very small north-south temperature asymmetry should be expected. Moreover, the northern hemisphere, although not illuminated, should emit as much energy (within one percent) as the southern hemisphere at this date. At a given latitude, extreme temperatures are reached at the equinoxes. At the poles, seasonal amplitudes of about 10 K in the upper stratosphere and 6 K at the 0.6 bar level are predicted, and the variation with time of the emission to space is found to be at most 20 percent. The atmosphere of Uranus appears to be characterized by very long radiative response times (mainly due to its cold temperature) which inhibit the large seasonal variations that one could otherwise expect in view of the high obliquity of the planet and its long orbital period.

We have developed a seasonal radiative model for the atmosphere of Uranus. It is in fact an adaptation of previous modeling for Saturn's stratosphere (Bezard and Gautier, 1985). In such a seasonal model, temperature for a given pressure level p and at a given time t is derived from the simple equation:

$$\frac{dT(p,t)}{dt} = \frac{mg}{C_p} \frac{dF(p,t)}{dp}, \quad (1)$$

where m is the mean molecular weight, g is the gravitational acceleration, C_p is the specific heat, and F is the net upward flux.

Temporal variation of temperature is then directly related to the variation of the total flux with pressure. The flux consists of two parts: the thermal flux essentially in the far-infrared ($\lambda > 7\mu\text{m}$), and the solar flux which is predominantly absorbed in the visible and near-infrared.

To compute the solar heating, we first consider absorption by methane bands (0.45-1.5, 1.7, 2.3 and 3.3 μm groups). Methane is constrained to follow the saturation law in the troposphere above the condensation level, and a constant mixing ratio is assumed above the temperature minimum. We also include deposition of solar flux by non-conservative aerosols located below the 0.5 bar level following the model of Bergstralh and Baines (1984).

The second part of the flux, the part concerned with thermal emission, is calculated through a multilayer monochromatic radiative transfer treatment for wavelengths longer than 7 μm . Calculations incorporate opacity due to CH_4 , $\text{H}_2\text{-H}_2$ and $\text{H}_2\text{-He}$ for a H_2 mole fraction of 0.90. This approach is quite different from that adopted by Wallace (1983) to model the seasonal variation of the thermal emission over Uranus' disk. Wallace's model is essentially a grey atmosphere model. Moreover, the use of the Rosseland mean opacity τ_R restricts its validity to deep atmospheric levels where $\tau_R \gg 1$, which corresponds to pressure higher than 1-2 bar.

When the calculated temperature profile is found to be unstable, the temperature lapse rate is set to the adiabatic value, and this criterion then defines the location of the convective zone. On the other hand, the internal heat flux behaves as a lower boundary condition in the calculation of the layer-by-layer transfer of energy. Three different assumptions have been investigated in this work. In the first case (1), the thermal structure in convective layers is not allowed to vary with time or latitude. Some meridional heat transfer thus takes place through the convective zone. In the second case (2), the heat flux is taken to be independent of latitude, and we adopted a value of $70 \text{ erg s}^{-1} \text{cm}^{-2}$ consistent with ground-based measurements. Such a model does not incorporate any kind of pole-to-equator transport of heat and will yield a thermal emission-to-space which is dependent on latitude. Finally, a third case (3) has been investigated in which a latitude-dependent heat flux is set at the base of the model so that the annual average of the emission-to-space does not vary over the disk. Meridional heat transfer thus occurs in the deep interior. Note that in any case horizontal advection of heat in the *radiatively-controlled* region is not taken into account. The model is also constrained to match some observational constraints: the Bond albedo $A_b = 0.35 \pm 0.05$, the effective temperature as measured from the Earth in 1977-1982 $T_e = 58.5 \pm 2 \text{ K}$, and a methane abundance $\text{CH}_4/\text{H}_2 \approx 0.03$ with large uncertainties.

The solid line in Fig. 1 indicates the synthetic temperature profile corresponding to an average over the southern hemisphere--the one which is presently sunlit--and was as well for year 1982.* That year, Moseley et al. (1985) made far-infrared measurements of Uranus, and the temperature profile they retrieved is displayed here as a dashed line. It is about 3 K warmer than the theoretical profile in the vicinity of the tropopause. This discrepancy may reveal the need for additional atmospheric heating at these levels, possibly by absorption of

*This is consistent with the conventional definition which identifies the pole corresponding to the direction of the positive angular momentum vector of rotation for Uranus as the South Pole because that vector direction is less than 90 degrees from the South Ecliptic Pole.

solar flux by dust particles as discussed by John Appleby in the preceding paper. The model exhibits a temperature minimum located around the 50 mb level with a very shallow lapse rate in the vicinity (10-100 mb). The temperature lapse rate reaches the adiabatic value near the 0.45 bar level, but it is noteworthy that it becomes subadiabatic again at the deepest layers of the model below the 1.5 bar level. In fact this special feature occurs because at these levels the solar flux no longer penetrates efficiently so that solar heating is negligible, and on the other hand the internal heat flux is too weak to maintain alone an adiabatic lapse rate. However, at even deeper layers corresponding to high far infrared optical depths, the lapse rate is likely to be adiabatic again for a non-zero internal heat flux.

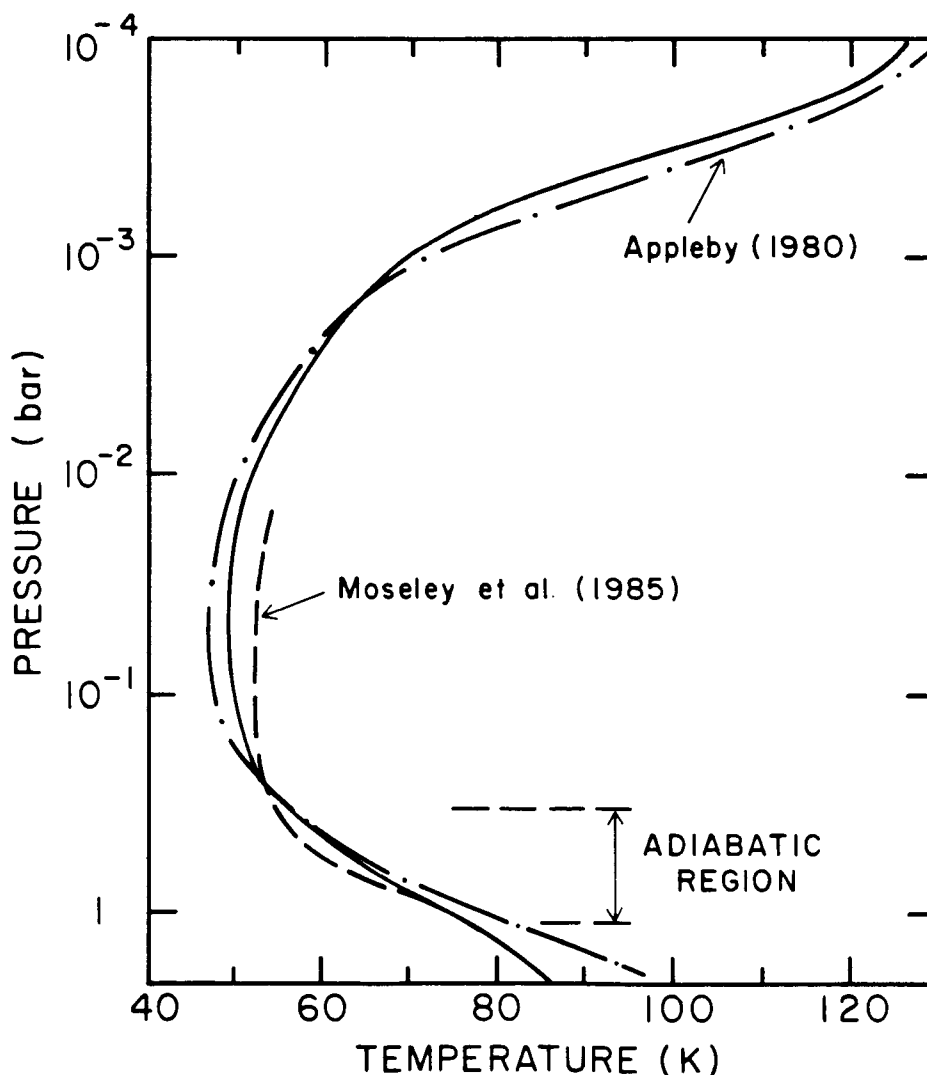


Figure 1. Synthetic temperature profile (solid line) corresponding to an average over the southern hemisphere compared to the result obtained by Appleby (1980) and the retrieved profile by Moseley et al. (1985).

When you perform ground-based spectrophotometry of Uranus to determine its effective temperature, a potential error might be introduced in that you measure the thermal emission of the sunlit hemisphere, which may differ from the global planetary emission. We have therefore compared, in the framework of this seasonal model, the actual planetary effective temperature to that measured from the Earth as a function of time. In Fig. 2 the curves labelled 1, 2 and 3 correspond to the above mentioned cases concerning the behavior of the internal heat source. The corresponding dashed lines indicate the expected seasonal variation of observations from Earth as estimated by our model. One can see that, at most, the discrepancy between the "true" and the "apparent" effective temperature is less than 2 K and thus lies within the typical uncertainties associated with ground-based measurements. The maximum discrepancy corresponds to no more than a 10 percent variation in the emitted flux; it is reached at the equinoxes, and in case 1 or 2 at the solstices to a lesser extent. We can then conclude that fortunately the inference of Uranus' effective temperature from ground-based studies is not too strongly biased despite the nature of the planetary seasonal cycle.

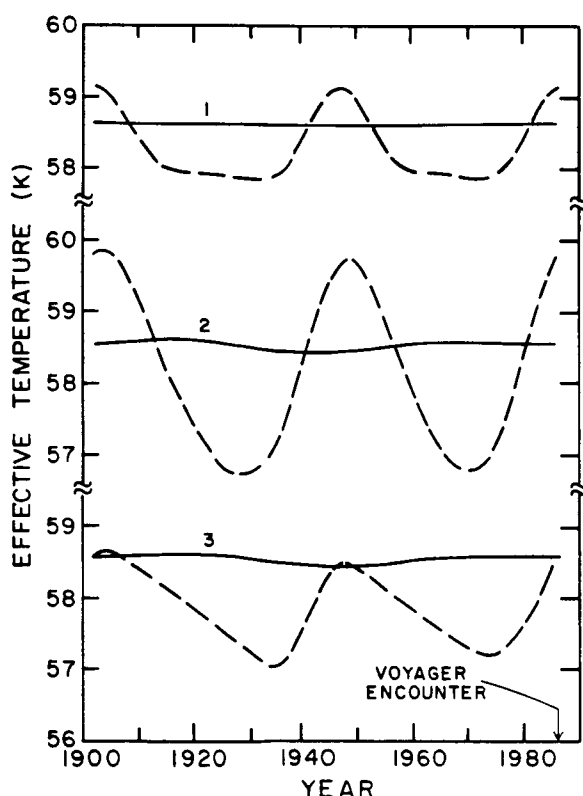


Figure 2. Seasonally dependent effective temperature for cases 1-3. The solid line curve indicates the actual planetary effective temperature, and the dashed line shows that predicted to be measured from Earth.

Figure 3 shows the predicted seasonal cycles of polar and equatorial temperatures for the 0.35 bar level for cases 1 and 2. This level is close to the emission-to-space level. Maximum seasonal variations occur at the poles with amplitudes at 0.35 bar in the range 1-3.5 K depending on the assumed redistribution of heat at deeper levels. Larger seasonal changes, typically 5-10 K, are predicted in the high stratosphere. The variation with time of the emission-to-space is at most 25 percent. At the equator, the 0.35 bar temperature does not vary by more than 0.1 K, and seasonal changes do not exceed 1 K at any atmospheric level. Two important characteristics should be noted. First, the seasonal cycle of the atmosphere is lagging behind the solar heating by approximately one-quarter of the orbital period, so maximum north to south asymmetry occurs at the equinoxes and minimum at the solstices. Secondly, the temporal variations of temperature are indeed very weak in view of the high obliquity of Uranus, its small internal heat source if any, and its long orbital period (84 years). These characteristics result from the very long radiative response time of the Uranian atmosphere mainly due to its cold temperature.

The Voyager 2 spacecraft encounters Uranus in January 1986, only four months after the summer solstice for the southern hemisphere. Because of the phase lag between the insolation cycle and the response of the atmosphere, very small north-south asymmetry should be expected. Within the atmospheric range which will be sounded by the infrared spectrometer IRIS (approximately 0.1-0.6 bar), the difference is expected to be less than 2 K at any level.

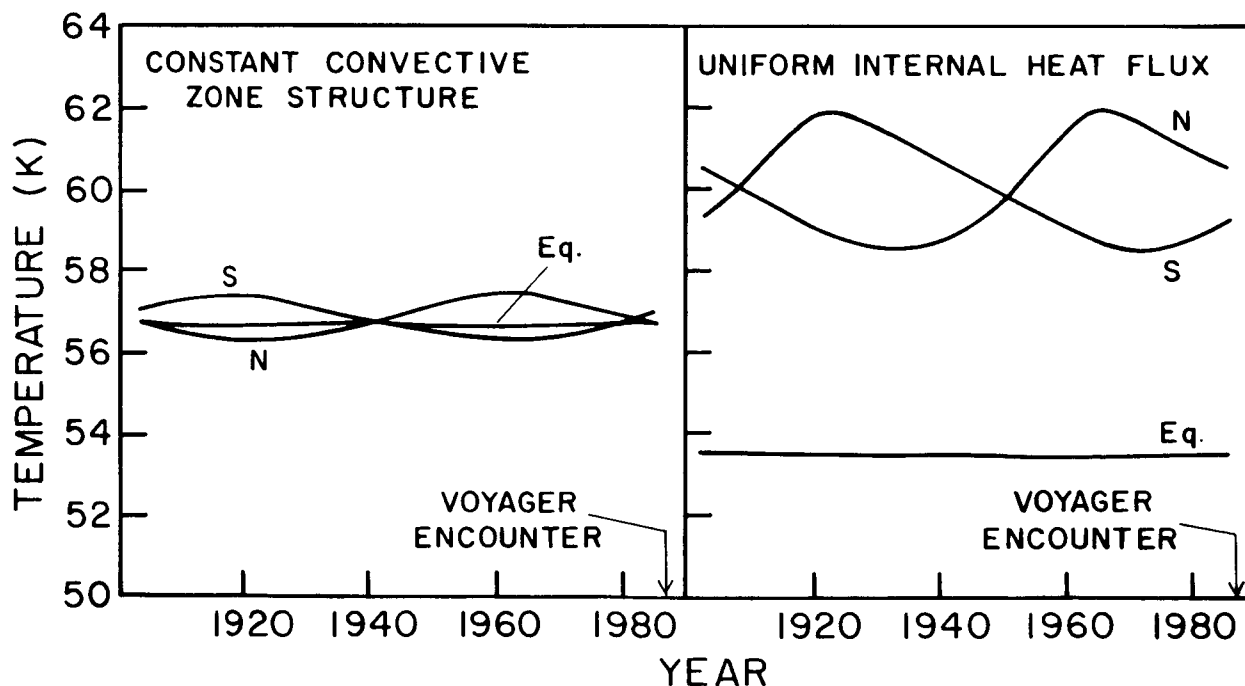


Figure 3. Predicted seasonal cycles of polar and equatorial temperatures for the 0.35 bar level for cases 1 and 2.

The lack of north-south asymmetry is also illustrated in Fig. 4 where the calculated local effective temperature is plotted as a function of latitude for the time of Voyager encounter. For any redistribution of heat at deep levels (case 1, 2 or 3), the two hemispheres are predicted to emit the same amount of energy within one percent. However, a pole-to-equator gradient as high as 6 K would result if no redistribution of heat takes place to compensate for the minimum insolation at low latitudes (case 2). This difference is less than 0.5 K if some transfer of energy takes place in the upper convective layers (case 1) or through the deep interior (case 3). Now, it only remains to be seen whether seasonal radiative models give a realistic representation of the actual thermal structure of Uranus. Undoubtedly, the forthcoming Voyager encounter will give important clues towards the answer to that question.

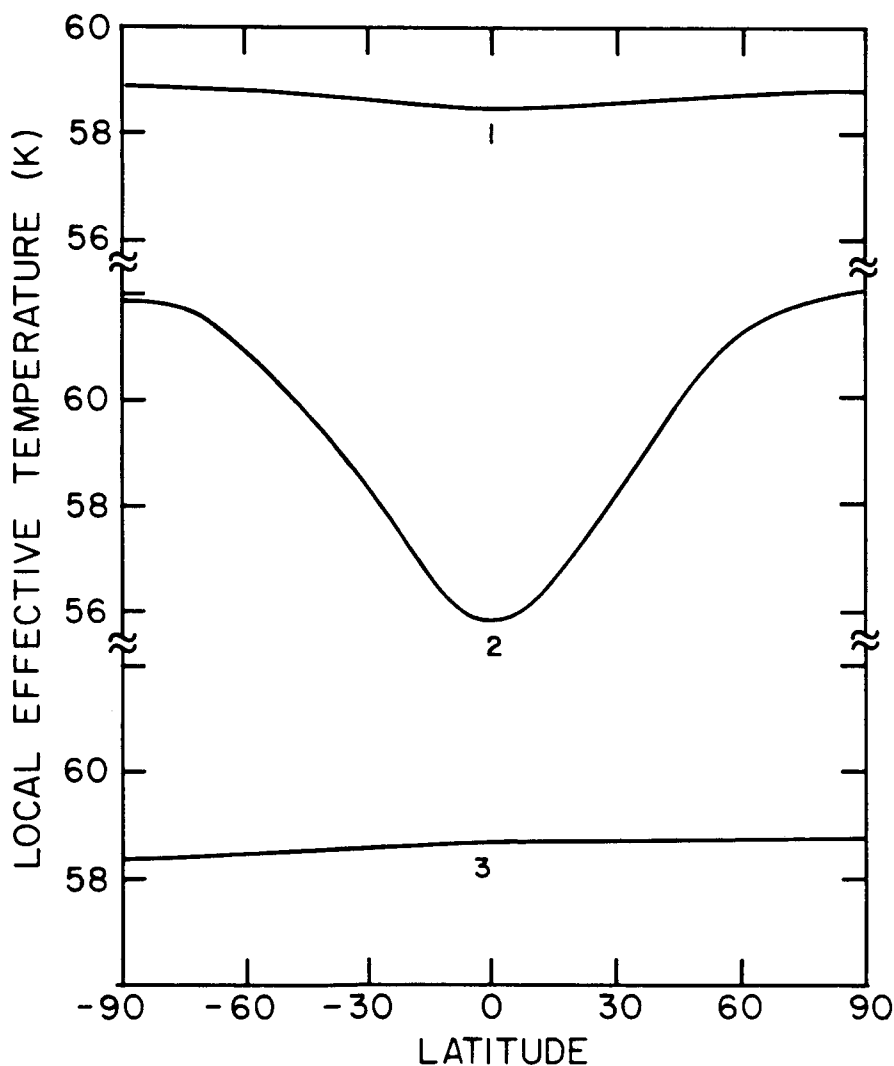


Figure 4. Local effective temperature for the three model cases as a function of latitude for the time of Voyager encounter.

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DR. STOKER: Isn't the radiative time constant, even at the levels you are looking at, longer than the seasonal time scale? How can you get seasonal variations, or how can you account for that by your models?

DR. BEZARD: Yes, in fact that was the problem. The radiative time constants are very long at any level. That is why you see only weak variations of temperature along the Uranian year. We still have some variation because there is a very long day and a very long night, and also a negligible internal heat flux.

DR. INGERSOLL: I think you are saying that the big variation in the middle curve (Fig. 4) is not a seasonal variation at all. It's just the Sun coming onto the equator and then the pole.

DR. BEZARD: Yes. There is no north to south asymmetry predicted for Voyager encounter.